Volume V

Appendix G.7

Starfire Team Final Report, Jun 3, 2003

This Appendix contains NSTS-37379 Starfire Team Final Report in Support of the Columbia Accident Investigation, 3 June 2003.

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NSTS-37379

Starfire Team Final Report

in support of the *Columbia* Accident Investigation

June 3, 2003

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Executive Summary

The Starfire Team was created in support of the STS-107 Orbiter Vehicle Engineering (OVE) investigation effort. The team's charter was to review imagery, both still photography and video taken at the Starfire Optical Range (SOR) at Kirtland Air Force Base in New Mexico, in order to determine the state of the orbiter at that time in its re-entry.

As part of this investigation about 18,800 video frames and 3 digital stills were reviewed and a small portion of these were processed and analyzed. All were categorized as to potential return of information regarding the condition of the orbiter. A total of ten anomalous optical signatures (AOS) were identified and images associated with these signatures were processed to some degree. An AOS here is considered to be a visual appearance of the orbiter containing a characteristic that appears irregular; i.e., lack of symmetry, pulsation, scintillation. Difficulties arose due to motion blur related to the relative motion of the orbiter and camera, failure to track due to relative angular velocity, lack of comparative nominal condition images, saturation of images, and lack of resolution. In some cases these difficulties were prohibitive in determining a conclusion regarding the condition of the orbiter.

Of the ten AOS, two were concluded to be nominal (with the understanding an off-nominal condition contribution was indeterminate for one image), two were not classifiable as nominal or off nominal, and six were considered off nominal. See Table 1 for a summary. Of the six AOS identified as off nominal, the Wing Leading Edge (WLE) "bulge(s)" is the single AOS for which a nominal condition is least likely. Other AOS have a possibility of finding a nominal condition, albeit one not currently understood, as the source. The lack of comparative nominal condition data precludes any conclusion to the one hundred percent certainty level. If all ten AOS are compared, five provide for the possibility of an event occurring relating to the left wing.

Recommendations for the future, in the event such imagery is requested, would require that higher resolution video be obtained at high magnification, such as that taken through a telescope that is capable of tracking an object with a high angular velocity. The digital stills proved useful, but a greater number would be desired, with minimal saturation. Nominal condition re-entry imagery is deemed necessary for future studies of this type of orbiter condition analysis upon re-entry.

1.0 INTRODUCTION

The Starfire Team was formed in support of the Orbiter Vehicle Engineering Working Group (OVEWG) to aid the NASA community in the investigation of the STS-107 accident. The team was formed with members of various organizations, some associated with NASA, some not. A short biography of each member can be found in Appendix B of this report.

The Starfire Optical Range (SOR), a part of the Air Force Research Lab, acquired three still digital photographs and four videos of the Columbia as it passed over Albuquerque, New Mexico on re-entry. This was the first attempt by SOR to capture imagery of a shuttle on re-entry. SOR acquired color video through a handheld digital camera operated in movie mode, one video through a camera mounted on the elevation gimbal of the coelostat used to track the orbiter and two videos with different fields of view obtained with two telescopes looking through the 1.0-m clear aperture coelostat consisting of two flat mirrors that rotate to view different parts of the sky. Three still digital photographs were also acquired with a 3.5-inch telescope and CCD camera, also looking through the coelostat, though one of the stills imaged only a small fraction of the orbiter/plasma trail.

These images were obtained by engineers at SOR volunteering their time and using available equipment. The data collection was not an official tasking. Tracking of the orbiter had never before been attempted with this equipment. The degree of potential object brightness was unknown and that, coupled with a brightening sky due to imminent sunrise, made gain adjustments (to prevent saturation) on the instruments difficult. There was no opportunity to compensate for errors in the supplied vectors of the orbiter as the orbiter was obscured by cloud during the first 20 degrees of the pass; this compounded the difficulty of tracking a rapidly moving object in a small field of view (FOV).

The Starfire Team was formed to process and evaluate the resulting imagery for indications of the orbiter condition at that time in the re-entry path. The Starfire Team reviewed all images and identified those stills or frames of the videos that appeared most probable to achieve this goal. The team focused on the identified video frames and stills and performed various levels of image processing and analysis.

The Starfire Team provided regular status briefings to the OVEWG.

2.0 PURPOSE & SCOPE

This report defines and documents the Starfire Team investigation: determination of important stills and video frames, problems encountered, data analysis techniques, and data interpretation results.

The scope of the data interpretation included a limited number of the available video frames and two of the three stills. While other video frames were available, those of the orbiter with AOS were judged the most potentially revealing and only those were examined in detail.

Classification of priority resulted in four categories:

1) High potential of information return from analyses
2) Moderate potential of information return from analyses
3) Low potential of information return from analyses
4) No expected information return from analyses

After review of all available data, two of the three stills and one set of frames from the 5-millirad field-of-view (FOV) video were considered to be Category 1. A set of frames here is defined as a sequential subset of video frames extracted from the complete video, wherein the number of frames in a set varies according to the content. The remaining still, one set of frames from the 5-millirad FOV video, and one set of frames from the 700-microrad FOV video were classified to be Category 2. The remaining video frames that contained views of the orbiter, as well as the two remaining videos were considered to be Category 3. Any set of video frames that failed to capture the orbiter in its field of view was classified to be Category 4.

Several problems were encountered. The primary difficulty with analysis was the lack of nominal-condition comparative data. Other problems were unknown plate scales (i.e. size of objects), motion blurring, saturated images, unknown orientation (rotation), and resolution. Techniques for analyzing this type of imagery existed only in a limited fashion; this specific type of data did not previously exist.

Plate scales and orientation of a few images were determined by imaging starfields at the known elevation and azimuth of the image and calculating the scale and degree of rotation.

Data analysis techniques and interpretation required drawing on assorted personnel with backgrounds in image data reduction and analysis, astronomical data reduction and analysis, wire cad modeling, aerothermal modeling, and extrapolation of aerothermal conditions to visual results.

3.0 DATA

All video and stills were reviewed by the Starfire Team as well as independently reviewed by the STS-107 Image Analysis Team creating the timeline for the Columbia's re-entry. The review by the timeline team was used as a metric against category classification. The approximate Greenwich Mean Time (GMT) coverage encompassing all of the videos and stills wherein the orbiter is visible is 13:56:31 – 13:58:12.

The two videos that were not acquired through a telescope were considered of no value for the purpose of this team's work other than to confirm or deny possible changes in appearance of the orbiter's luminosity. These were videos EOC2-4-148-2 and EOC2-4-148-6. They were reviewed for possible changes in luminosity and no changes were seen that correlated with any AOS.

Video EOC2-4-148-4 is a 5 millirad FOV (~1/3 degree) digital video taken through a 14" Celestron telescope looking off two 1.5-m diameter flat mirrors positioned at 45 degrees to the line of sight that rotate about vertical and horizontal axes: a configuration known as a 1-m clear aperture coelostat. This arrangement causes images in the focal plane of a camera to rotate as the mount tracks objects across the sky. Sets of frames ranged from Category 1 through Category 4. The orbiter was in the FOV intermittently.

Video EOC2-4-148-3 is a 700 microrad FOV video taken through a 7" Questar telescope also looking through the 1-m coelostat. Sets of frames ranged from Category 2 through Category 4. The orbiter was in the FOV infrequently.

Digital stills consist of JSC2003e03394 (GMT 13:57:14) and JSC2003e03395 (GMT 13:57:59). These were acquired with a 3.5-inch telescope and CCD camera, also looking through the coelostat. Both of these stills were classified Category 1. The third still (GMT 13:57:51) has been submitted for inclusion in the JSC Columbia Accident stills database, but as of yet has no JSC number. It was classified a Category 2. All three stills were taken with a CCD camera attached to a 3.5-inch Questar telescope looking through the 1.0-m coeleostat.

Appendix C identifies categorization of this data in both pre- and post- analysis status.

4.0 DATA ANALYSIS

After preliminary review and classification, those stills or sets of video frames in Categories 1 and 2 were examined. Sets of video frames were captured via two different programs ISEE & DPS Reality. Late in the analysis it was recognized that some small degree of signal was lost if video frames were taken from a second-generation copy rather than a digital clone or digital copy of the original. Video frames taken from a digital copy were examined and while slightly higher in quality, appeared to add no significance to the final results, thus the data were not reprocessed.

Adobe Photoshop was used to enhance contrasts, rotate images as required to correct to proper orientation due to the rotation of the mirror, and crop images. (Adobe resamples an image when it rotates an image; resampled images were not used in for final analysis.) Preliminary interpretation was performed. Stills and some single frames of video were processed with an iterative blind deconvolution method (Center for Adaptive Optics, Christou). Two of the stills were also processed using a regularized maximum likelihood method (Veridian, Thelen). Only the stills and frames processed by the blind deconvolution method were interpreted and then reviewed by the entire team.

After a detailed review, many images were reclassified. See Appendix C for details regarding classification/reclassification and a brief summary of results.

5.0 RESULTS

The Starfire Team reviewed about 18,800 frames of video and three digital stills. Ten possible AOS were identified and investigated. Due to the lack of comparative nominal condition imagery, in no case can an apparent AOS be confirmed to the one hundred percent level of certainty. One event not addressed here is Debris 16, a debris event noted

Anomaly	NASA # Video/Still	Conclusion
Turbulence near the nose/left wing, WLE	EOC2-4-0148-3	Unknown if off-nominal
Asymmetric gas trail	JSC2003e03394	Nominal
WLE "bulges"	JSC2003e03394	Off-nominal
Asymmetric bulge at nose	JSC2003e03394	Nominal
Asymmetric streaming of gas from aft of orbiter	EOC2-4-0148-4	Unknown if off-nominal
Flare 1	EOC2-4-0148-4	Off-nominal
Flare 2	EOC2-4-0148-4	Off-nominal
Flaring/Streaming	EOC2-4-0148-4	Off-nominal
Brightening of left wing	JSC2003e03395 EOC2-4-0148-4	Off-nominal
Nose or Tail brightening	JSC2003e03395 EOC2-4-0148-4	Off-nominal

Table 1 – Anomalous Optical Signature (AOS) Results

by the STS-107 Image Analysis Team constructing the timeline. The debris event is difficult to see and was not part of the scope of this task. Of all the AOS identified as off nominal, the Wing Leading Edge (WLE) "bulge(s)" is the AOS for which a nominal condition is least likely. Other AOS have a greater possibility of finding a nominal condition, albeit one not currently understood, as the source. See Table 1 for a list of the ten AOS, video/still the AOS is associated with, and conclusions. A brief discussion follows, identifying possible causes of the AOS identified and the conclusions drawn. Some additional information is contained in Appendix D.

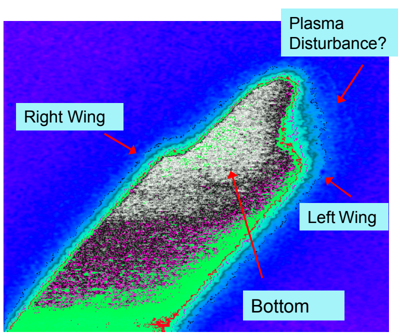


Fig. 1: Turbulence near the nose/left wing/WLE. NASA video EOC2-4-0148-3. It is unknown what a nominal optical signature of the flowfield at these specific conditions (speed, orientation, etc.) would look like. The signature is not overt nor does telemetry provide additional insight. No conclusion can be drawn regarding a nominal or off nominal condition.

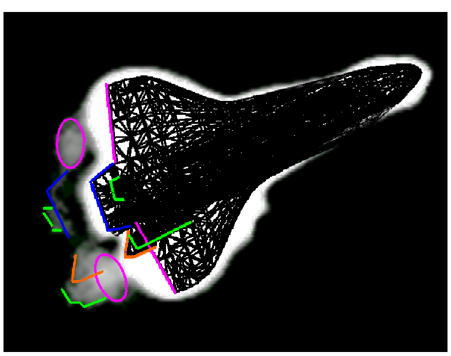


Fig. 2: Asymmetric Gas Trail. NASA Image JSC2003e03394. The processed image revealed structure in the gas trail. This structure could be correlated to specific source locations on the orbiter. Damage to the left wing could create additional enhancement of the gas trail that could not be distinguished from known sources. This optical signature is considered to represent a nominal condition with the caveat that an off-nominal condition could not be identified as such with this image.

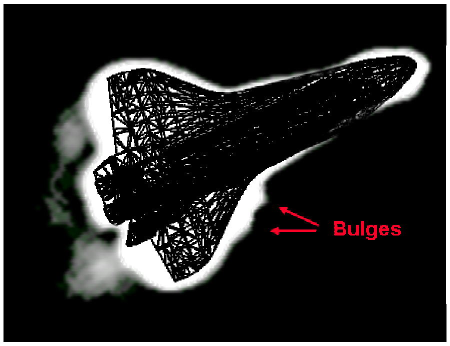


Fig. 3: WLE "Bulges". No currently understood nominal condition can support this optical signature. Possibilities for sources of this optical signature are: localized increase in temperatures (hot spots), local increase in reflectivity (unlikely), tile damage (unlikely), and damage to WLE. Viewing geometry and refraction could contribute. See Appendix D for some additional explanation. This is considered to represent an off-nominal condition.

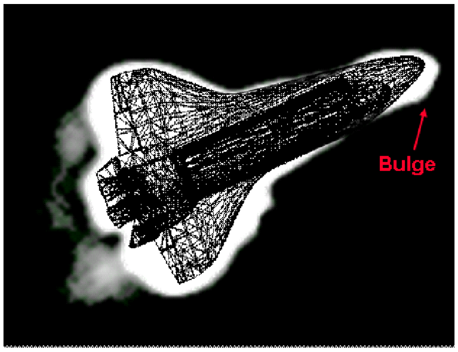


Fig. 4: Asymmetric Bulge at Nose. The nose is known to be the hottest spot and could produce an optical signature representative of a localized intensity increase. As the image displays the bottom of the orbiter (the wirecad model is "see-through" and somewhat misleading due to that), orientation and viewing angle is considered the most likely source of this optical signature. This is not inconsistent with Sandia's Plasma models. This is considered to represent a nominal condition.

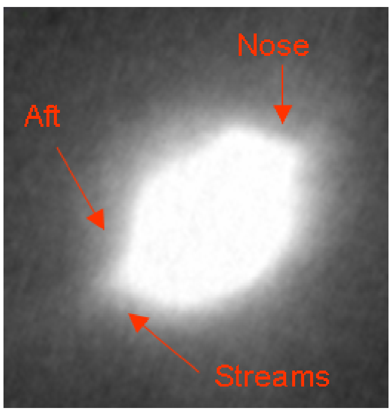


Fig. 5: Asymmetric Streaming of Gas from Aft of Orbiter. NASA video EOC2-4-0148-4. This is apparent in the video and not well represented by a still image. In the video, the image of the orbiter is highly saturated and is "lemon-shaped" in appearance. The image shown at the left has been rotated into its approximate correct orientation and would appear similar to the above digital still were it not so badly saturated. A "tail" of gas/plasma is evident at the aft of the orbiter (identified as "streams"). This tail appears to stream and pulse over time. One of the three digital stills is acquired during this period of time and shows an asymmetric gas trail (see Fig. 2). This streaming is likely related to the asymmetric gas trail seen in the still and the explanation for the asymmetric gas trail potentially applies to this streaming/pulsing tail. The asymmetric gas trail in the still is thought to be nominal (with consideration of the caveats mentioned in Fig. 2) and this suggests that this streaming effect may also represent a nominal case. Without nominal comparative data, no conclusion can be drawn regarding if this is a nominal or off nominal condition.

The last five AOS are to some degree interrelated. The five signatures are Flare 1, Flare 2, Flaring/Streaming, Brightening of Left Wing, and Nose or Tail Brightening. The Brightening of the Left Wing and Nose or Tail Brightening occurs simultaneously with Flare 1 and visually may help create the optical signature of Flare 1. Flare 1 shows brightening of the left wing, the nose/tail, and a streaming signature (hot gas?) possibly located around the tail region. This does not imply tail damage, but rather one possibility presented is that normal tail interaction with the flowfield generates this optical signature. The general optical signature of Flare 1 persists (in time) and Flaring/Streaming is seen. The orbiter passes out of the FOV, then returns. As it leaves the FOV again, Flare 2 is seen. Flare 2 is merely a brightening with no significant change in the general optical signature associated with Flare 1, other than the increase in brightness. Only the imagery of Flare 1 is shown as all five optical signatures are essentially represented by the three images shown below.

Fig. 6: Flare 1. NASA video EOC2-4-0148-4. Flare 1 is noted on the timeline for Columbia's re-entry and its AOS may in part be a brightening of the upper portion of the canopy and left wing of the orbiter. Images taken from the video are shown. To the left is the pre-flare appearance of the orbiter; to the right is Flare 1. The checkerboard pattern to the left of both images is the edge of the FOV. These images are approximately half a second apart in time. They have not been rotated to the proper orientation. Diffraction was considered as a possibility; diffraction is an effect of the optics seen as a brightening of an object as an object leaves the FOV of the telescope. This was tested for by SOR. Jupiter was used to represent the orbiter, as Jupiter was approximately the same visual size as the orbiter; the telescope was moved rapidly to simulate the orbiter's motion through the FOV. No similar brightening was noted. Although phase angle cannot be simulated (the orbiter was in daylight at the time), diffraction as the source of brightening is considered unlikely. The streaming of what is thought to be hot gas is not well represented by a still, but the aspect of the elongation of what may be hot gas can be seen in the digital still (Fig 6A), and contributes to the optical signature of Flare 1. Viewing angle may contribute to the signature seen in that the camera is viewing the aft of the orbiter. It is unknown to what degree the view is looking through a plasma trail, the opacity of the plasma trail, and if the plasma trail contributes to the "flare" signature. Additionally, shadowing due to phase angle of the sun may contribute to the signature.

Fig. 6A: Flare 1. NASA image JSC2003e03395. The second digital still analyzed was taken at about the same time as the right-hand image in Figure 6. The still is shown here after a blind deconvolution has been applied to the image and its contrast enhanced. It has been properly oriented and displays a wireframe overlay of the orbiter. The wireframe overlay has been approximately scaled. Exact placement relative to the image is unknown. See Appendix D for more details regarding these images and others. The flare image and the digital still are considered to represent an off-nominal condition, and all five AOS listed in the paragraph above Fig. 6 are considered off nominal.

6.0 CONCLUSIONS

Of the ten AOS identified in the Starfire datasets, two were classified as nominal, two were inconclusive and six were considered potentially off-nominal, with one of those six having no currently identifiable possibility of a nominal condition. If all ten AOS are compared, five provide for the possibility of an event occurring relating to the left wing. Based upon the AOS with no currently identifiable possibility of a nominal condition, the left wing WLE appears to be in an off-nominal state.

7.0 RECOMMENDATIONS

Recommendations for the future, in the event such imagery is requested, would require that higher resolution video is obtained at high magnification, such as that taken through a telescope that is capable of tracking an object with a high angular velocity. Resolution, saturation, and tracking were three keys issues that reduced the usefulness of the videos. An additional issue was that, due to the rotating coelostat, the orientation (rotation) of each frame of video was unknown and each processed frame's rotation had to be determined by acquiring starfield images at a later date. The digital stills proved useful, but a greater number would be desired, with minimal saturation.

Nominal condition re-entry imagery is deemed necessary if future comparative studies of this type of orbiter condition upon re-entry analysis is requested or planned.

APPENDICES

APPENDIX A
ACRONYMS AND ABBREVIATIONS

AOS	**Anomalous Optical Signature**
FOV	**Field of View (telescope)**
GMT	**Greenwich Mean Time**
OVE	**Orbiter Vehicle Engineering**
OVEWG	**Orbiter Vehicle Engineering Working Group**
SOR	**Starfire Optical Range**
WLE	**Wing Leading Edge**

APPENDIX B
TEAM MEMBER BIOGRAPHIES

Starfire Team Biographies

Julian Christou
Dr. Christou has over twenty years experience with image processing of both astronomical and artificial satellites. He obtained a Ph.D. in Astronomy from New Mexico State University and has worked at the National Optical Astronomy Observatories and Steward Observatory both in Tucson, Az., as well as the Starfire Optical Range. He is presently a research scientist with the Center for Adaptive Optics at the University of California, Santa Cruz.

Rick Cleis
Mr. Cleis works at the SOR. No Bio provided.

Robert Q. Fugate
Dr. Fugate is the Air Force Senior Scientist for Atmospheric Compensation and serves as the Technical Director, Starfire Optical Range, Directed Energy Directorate, Air Force Research Laboratory, Kirtland Air Force Base, N.M. The Range operates 1.5- and 3.5-meter telescopes, and a 1.0-meter beam director. Dr. Fugate conducts a research program on atmospheric propagation physics; atmospheric compensation using laser guide star adaptive optics; the acquisition, tracking and pointing of lasers to earth-orbiting satellites; and the development of sensors, instrumentation and mount control of large-aperture, ground-based telescopes. He has worked for the U.S. Air Force since 1970 in the fields of atmospheric propagation, electro-optical sensors and detection, space surveillance and adaptive optics.

Dewey Houck
Mr. Houck is currently a Senior Technical Fellow working in the Space and Intelligence Systems Division of IDS for Boeing/Autometric. He chairs Boeing/Autometric's Engineering Review Board that acts in an oversight capacity for Product Development and Program initiatives. He also chairs the Technology Steering Group responsible for commercial product investment decisions. Prior to the Boeing acquisition (of Autometric), he served as a member of the senior management team as Vice President for Technology development for Autometric. During that time, he administered all Research and Development activities including several geospatial, photogrammetric and visualization initiatives. Mr. Houck has Master's and Undergraduate degrees in Civil Engineering from Virginia Tech with specialization in Photogrammetry and Geodesy.

Kandy Jarvis
Ms. Jarvis has seven years experience at NASA, all with Lockheed Martin Space Operations. Her position is Senior Research Scientist as Lead for the Planetary Astronomy Group and Optical Lead for the Orbital Debris Program Office. In both positions she works with a variety of telescopic data, including the acquisition, data reduction, analysis, and interpretation of spectrophotometry and video and short exposure (5 – 20 seconds) images of starfields containing orbital debris.

Robert Johnson
Major Johnson is with the USAF and has a PhD. He works with cameras and optics. No Bio provided.

Roger Petty
Mr. Petty works at the SOR. He is an optical engineer. He performed as outdoor spotter and operated the handheld camera. No Bio provided.

Rich Rast
As an Air Force civilian, Mr. Rast served as chief orbital analyst at NORAD before coming to JSC in 1986. He left JSC after six years to become operations manager of SOR. He now works at AFRL's Satellite Assessment Center. He proposed that SOR image Columbia's re-entry to JSC-DM4's Gilman on December 9, 2002.

Karen Watts
Ms. Watts has six years of experience in the Space Shuttle Program, all with the United Space Alliance. Her current position is Pointing Operations Engineer in the Attitude and Pointing Office. The Pointing Office is responsible for manned spacecraft attitude determination and line-of-sight analysis.

R. Douglas White
Mr. White is currently the Director for Operations Requirements in the United Space Alliance Orbiter Element department. He began work on the space shuttle program in 1979 as an employee for Rockwell International in Downey, California. Mr. White has held increasingly responsible positions within the space shuttle program focusing on the areas of turnaround test requirements, engineering flight support, anomaly resolution, and Orbiter certification of flight readiness preparation. He joined United Space Alliance as a director in 1996. He holds a BS and MS in physics from UCLA.

Other Contributors:
Gil Carman: JSC NASA
Sina Farsiu: Engineering Department, Univ. of CA, Santa Cruz
Dr. Peyman Milanfar: Electrical Engineering Department, Univ. of CA, Santa Cruz
Scott Murray: JSC NASA
Dr. Brian J. Thelen: Veridian Systems Ann Arbor Research and Development Center

APPENDIX C
CATEGORY CLASSIFICATION AND SUMMARY

Type: Digital Still Photograph

NASA Number: JSC2003e03394
GMT Time: 13:57:14
Initial Classification: Category 1
Post Analysis: Category 1
Description: Saturated image of the underside of the orbiter.
Results: Image was analyzed, interpreted, and results presented. See Appendix D.

NASA Number: JSC2003e03395
GMT Time: 13:57:59
Initial Classification: Category 1
Post Analysis: Category 1
Description: Partially saturated image of the orbiter looking at the aft end.
Results: Image was analyzed, interpreted, and results presented. See Appendix D.

NASA Number: JSC2003exxxx (Still #3)
GMT Time: 13:57:51
Initial Classification: Category 2
Post Analysis: Category 3-4
Description: Plasma trail directly aft of orbiter.
Results: Image was analyzed and interpreted. Little to no information obtained.

Type: Video

NASA Number: EOC2-4-0148-2
Field of View: 5 degree
Frame Subset or Full Video?: Full Video
GMT Timespan: 13:56:47.22 – 13:58:11.29
Initial Classification: Category 3
Post Analysis: Category 3
Results: Video was reviewed. No significant anomalies seen other than those identified by the STS-107 Image Analysis Team. One piece of debris identified by the STS-107 Image Analysis Team: Debris 16. No further processing performed. Possibility of identifying additional debris with extensive processing of video.

NASA Number: EOC2-4-0148-6
Field of View: ~5 degree, RGB (color)
Frame Subset or Full Video?: Full Video
GMT Timespan: ~13:56:47 – 13:58:12
Initial Classification: Category 3
Post Analysis: Category 4

Results: Video was reviewed. No anomalies seen. No further processing performed.

Type: Video (cont.)

NASA Number: EOC2-4-0148-3
Field of View: 700 µrad
Frame Subset or Full Video?: Frame Subset
GMT Timespan: 13:57:23.0 – 13:57:23.3
Initial Classification: Category 2
Post Analysis: Category 2
Results: Video frame set = 7 fields (2 fields per frame, 29 frames per second). Video frames show motion-blurred orbiter. Effort was made to re-integrate images but relative velocity of orbiter and movement of camera prevented this effort. Field b, at GMT 13:57:23.1 was analyzed and interpreted. Results presented. See Appendix D.

NASA Number: EOC2-4-0148-3
Field of View: 700 µrad
Frame Subset or Full Video?: Full Video
GMT Timespan: 13:56:45.29 – 13:58:57.5 (excluding previously listed times)
Initial Classification: Category 3
Post Analysis: (Predominantly) Category 4
Results: Video was reviewed. In most frames, orbiter is not in the FOV. Occasional streaks of light suggest orbiter presence in or near the FOV. No further processing performed.

NASA Number: EOC2-4-0148-4
Field of View: 5 mrad
Frame Subset or Full Video?: Frame Subset
GMT Timespan: 13:57:11.14 – 13:57:18.3
Initial Classification: Category 2
Post Analysis: Category 3
Results: Video was reviewed. Includes time coverage of still JSC2003e03394. Orbiter is badly over-saturated; orbiter appears "lemon-shaped". An undefined asymmetric streaming is seen at aft of orbiter; may relate to tail of orbiter; unknown if nominal or off nominal. Severe saturation prevents further analysis at this time. No further processing performed.

NASA Number: EOC2-4-0148-4
Field of View: 5 mrad
Frame Subset or Full Video?: Frame Subset
GMT Timespan: 13:57:49.23 – 13:58:01.11
Initial Classification: Category 1
Post Analysis: Category 2-3
Results: Video was reviewed. Includes time coverage of still JSC2003e03395. Orbiter is partially over-saturated; orbiter appears "horseshoe-shaped". Aft of orbiter is toward camera. Two brightening events are seen to occur; these events are termed "Flare 1" and "Flare 2" in the timeline. Three hundred plus frames were extracted and processed with various methods by the CFAO. The orbiter is in and out of the FOV during this timespan. Two frames (13:57:54.14, 13:57:54.22) at the beginning of Flare 1 and peak of Flare 1 were analyzed and results presented; see Appendix D. No significant improvement was achieved

on most processed frames. Possibility of determining if the Flares are an optical effect related to the tail or nose with further study.

Type: Video (cont.)

NASA Number: EOC2-4-0148-4
Field of View: 5 mrad
Frame Subset or Full Video?: Full Video
GMT Timespan: 13:56:48.26 – 13:58:01.11 (excluding previously listed times)
Initial Classification: Category 2-4
Post Analysis: Category 3-4
Results: Video was reviewed. Orbiter is in the FOV intermittently. Excluding previously noted framesets, orbiter is motion blurred due to relative velocity of orbiter and motion of camera. No further processing performed.

APPENDIX D

Presentation 1: Select slides taken from first presentation to OVEWG
Presentation 2: Second presentation to OVEWG

Presentation 1

SPACE SHUTTLE PROGRAM
Space Shuttle Vehicle Engineering Office
NASA Johnson Space Center, Houston, Texas

Starfire Optical Range Location	Presenter: **Doug White**
	Date: Mar 3, 2003 — Page **6**

Preliminary

Location: Kirtland Airforce Base, NM

GMT coverage for the 5 deg fov: 13:56:47.22 – 13:58:11.29 (+/- 2 secs)

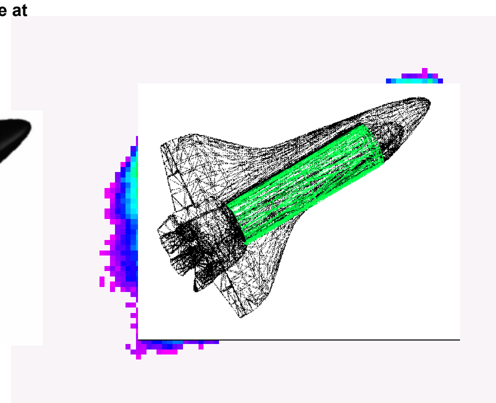
SPACE SHUTTLE PROGRAM
Space Shuttle Vehicle Engineering Office
NASA Johnson Space Center, Houston, Texas

Still at 13:57:14	Presenter: **Doug White**
	Date: Mar 3, 2003 — Page **11**

Preliminary

- Columbia observed from SOR, 1 Feb 2003, 13:57:14 UTC with Orbiter Attitude Overlay

Solid 3-D Model of Orbiter Attitude at 1 Feb 2003, 13:57:14 UTC (provided by E. Cross and A. Wheaton/SF5)



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SPACE SHUTTLE PROGRAM
Space Shuttle Vehicle Engineering Office
NASA Johnson Space Center, Houston, Texas

Stills at 13:57:51 and 13:57:59

Presenter: Doug White
Date: Mar 3, 2003
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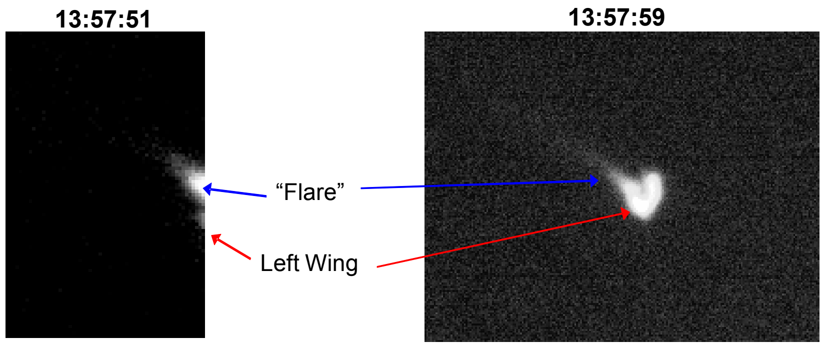
Preliminary



- Left Wing Is Visible in 13:57:59 Image
- Further Processing Is Underway
- Potential to Enhance Left Wing Chine and Left Wing Glove
- "Flare" Is Visible in Both
- Orientation Provided But Not Confirmed; these images are not yet corrected for orientation.

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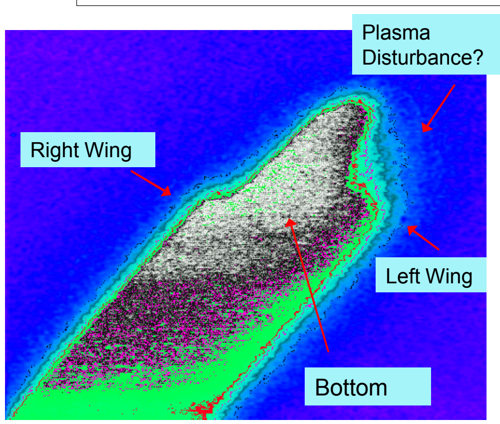
Image Taken from 700 mRad Video, GMT 13:57:23

Presenter: Doug White
Date: Mar 3, 2003
Page 21

Preliminary



- Colors represent pixel values No processing was performed other than the intensity highlighting
- Left wing chine and glove are not visible at this viewing angle
- Apparent disturbance seen in leading plasma
- Indeterminate significance at this time
- No nominal shuttle re-entry images exist for comparison

Image has been cropped and pixel intensity modified to bring out detail

Orientation unknown

Viewing bottom of orbiter

Presentation 2

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STS-107 Investigation
Kirtland Photo Tiger Team
4/21/03

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Objective and Team Members

Presenter Kandy Jarvis
Date April 21, 2003 Page 2

Preliminary

- The Objective of This Tiger Team Was to Analyze the Still and Video Images Taken at the Starfire Optical Range (Kirtland AFB, NM) During the STS-107 Entry

- Tiger Team Members
  - Doug White, USA
  - Kandy Jarvis, Lockheed Martin
  - Dewey Houck, Boeing
  - Karen Watts, USA
  - John Neer, Lockheed Martin
  - Scott Murray, NASA

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Starfire Optical Range Team and Media

Presenter Kandy Jarvis
Date April 21, 2003 Page 3

Preliminary

- Starfire Optical Range Team
  - Major Robert Johnson, PhD, camera and optics
  - Mr. Rick Cleis, software and coelostat control
  - Mr. Roger Petty, optical engineer, outdoor spotter and handheld camera operator
  - Mr. Rich Rast, liaison with NASA to get vectors
  - Dr. Robert Q. Fugate, Senior Scientist and Technical Director, S OR (Unable to be there during the event)
- Media
  - 4 videos
  - 3 stills
  - A total of 5 cameras were used, some utilizing telescopes, some not

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Images Analyzed

Presenter Kandy Jarvis
Date April 21, 2003 Page 4

Preliminary

Revised Analyses of Starfire Optical Range Stills

13:57:14

13:57:59

Two Frames Taken from 5-mRad Video for Analyses

13:57:54.14

13:57:54.22

Stills and frames have been processed by Dr. J. Christou, Center for Adaptive Optics, UCSC using a blind deconvolution technique

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Starfire Optical Range Stills & Frames

Presenter Kandy Jarvis
Date April 21, 2003 Page 5

Preliminary

- Stills:
  - 3.5” telescope looking through a computer controlled 1.0 -m coelostat (rotating mirror)
  - The plate scale is known for these images
    - ~ Measurements of object can be done
    - Re-processing has altered plate scale
  - Orientation (rotation) is known
  - The stills have an ~5 mRad (~1/3 degree) field of view (fov)
- Video Frames:
  - 5 mRad fov: intensified CCD camera attached to a 14” telescope, looking through the 1.0-m coelostat
    - Orientation for every frame will change
    - Approximate Orientation known
  - Plate scales have been estimated
    - Re-processing has changed the plate scale

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Still at 13:57:14

Presenter Kandy Jarvis
Date April 21, 2003 Page 6

Preliminary

- Notes Regarding Attitude Comparison at Time: 1 Feb 2003, 13:57:1 4 UTC
  - Models account for 8 degree rotation (per 24 -Feb. SOR e-mail)
  - Elevons, body flap, and engines are modeled in neutral position
  - Groundsite observer viewing from slightly port, slightly forward of normal to orbiter belly
  - Model scales were done visually
    - Approximations were calculated based on wingtip to wingtip dista nce and nose to tail distance
    - Plate scale of original known; compared to deconvolved image and plate scale approximated
    - Model fit visually based upon approximated scale and compared ag ainst SOR’s model

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Still at 13:57:14

Presenter: Kandy Jarvis
Date: April 21, 2003
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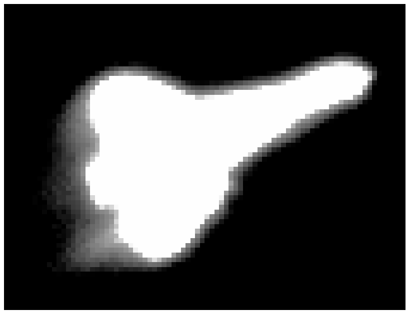
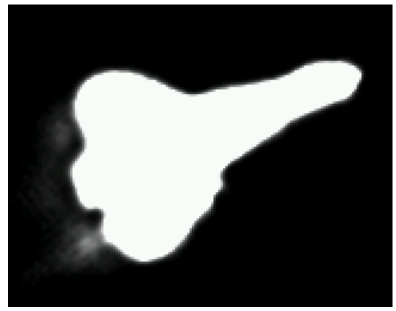
Preliminary



Raw Image



Re-Processed Image

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Still at 13:57:14

Presenter: Kandy Jarvis
Date: April 21, 2003
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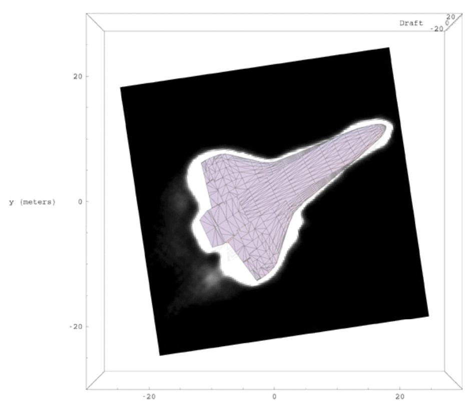
Preliminary



Starfire Optical Range Image (26 March 2003)
model overlay (R. Cleis, R. Fugate, R. Johnson)
image sharpened using deconvolution (J. Christou)

The model scaling and orientation are based on telemtery (latitude, longitude, and altitude from NASA) and observations (azimuth, elevation, and range from SOR). The image scaling and orientation were derived from measurements using star fields. The Columbia model was provided by NASA.

Mathematically scaled wireframe model overlain on re-processed image

•Model scaling based on telemetry

•Image scaling based on starfield measurements

The side of the orbiter and the tail were decreased in brightness in this overlay

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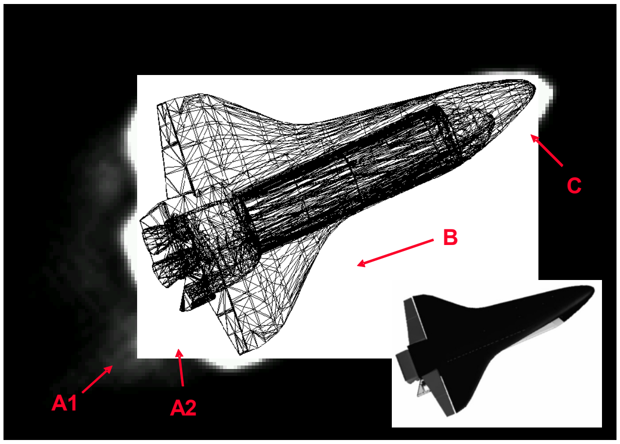
Presenter Kandy Jarvis
Date April 21, 2003 Page 9

Still at 13:57:14

Preliminary



Wire frame 3-D Model of Orbiter Attitude at 1 Feb 2003, 13:57:14 UTC overlaid on still
Solid 3-D model provided as inset

3 Areas of Interest

- Asymmetric (A) Gas Flow Pattern
  - Left wing more elongated in vertical wake (A1)
  - Greater area brightened in aft wing area (A2)
- Asymmetry (B) of Wing (Left vs. Right)
  - Convex in region (Xo-1100, Yo-256), leading edge of left wing.
- Asymmetry (C) of Nose

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Still at 13:57:14

Preliminary

Asymmetric Gas Flow (A1)

- When the re-processed image is adjusted to brighten the fainter pixels, details of the asymmetric gas are definable
  - Correlation between portions of the orbiter and the gas are possible
- The most probable correlations are presented
  - Other possibilities are not precluded and should be investigated by
    - •Modeling
    - •Wind tunnel testing
- Specifics of correlations follow

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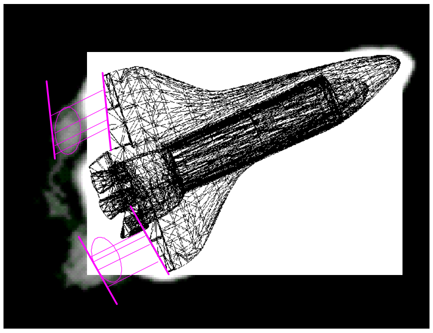
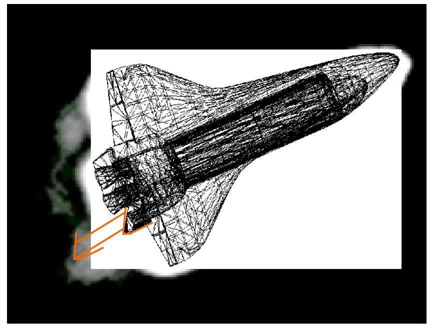
Still at 13:57:14
Gas correlation

Presenter **Kandy Jarvis**
Date April 21, 2003 Page **11**

Preliminary





- Gas (elliptical circles) seen behind right wing
  - •Assumed nominal
  - •Assumed symmetric w/respect to left wing
- Gas flow from the tail identified

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Still at 13:57:14
Gas Correlation

Presenter **Kandy Jarvis**
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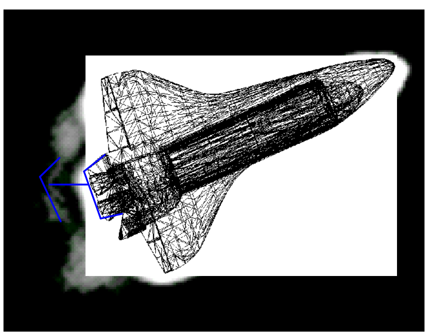
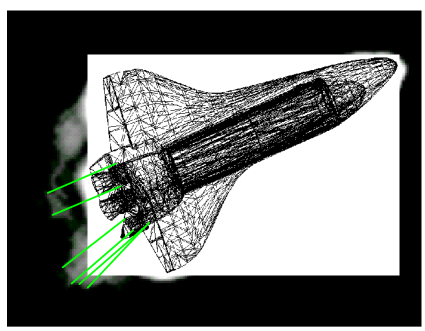
Preliminary





- Gas flow from the body flap identified
- Gas flow from the OMS pods suggested as explanation
- See next page for additional options

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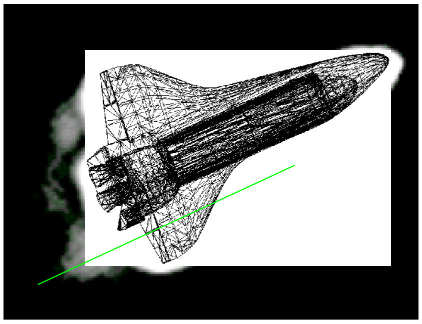
Still at 13:57:14
Gas Correlation

Preliminary



- **Flow from split between inboard and outboard elevons?**
  - Symmetry expected but not seen
  - Unlikely
- **Elevon position**
  - Right and left elevons are between 0.3 and 0.7 degrees different in position between 13:57:14.0 – 13:57:14.99
  - Unlikely but could contribute
- **"Bulges" in leading edge create turbulence and/or hot gas**
  - This possibility cannot be ruled out
  - Potential resultant gas flow should be modeled
- **Viewing geometry and refraction could contribute**

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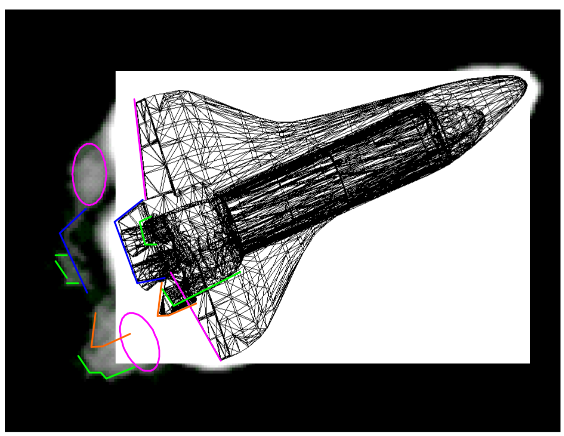
Still at 13:57:14
Gas Correlation

Preliminary



Correlation of Gas

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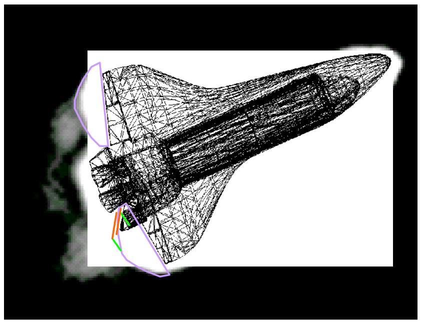
Preliminary



Greater area is brighter behind trailing edge of left wing (A2)

- Both wings show a gas flow pattern that is rounded; however, left wing has an additional bulge in area near elevon gap
- This brightened zone appears to correlate with the tail and left OMS pod/stinger
  - Some contribution could be from either the elevon, or from the "bulges" along the leading edge of the wing

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Still at 13:57:14	Presenter: Kandy Jarvis
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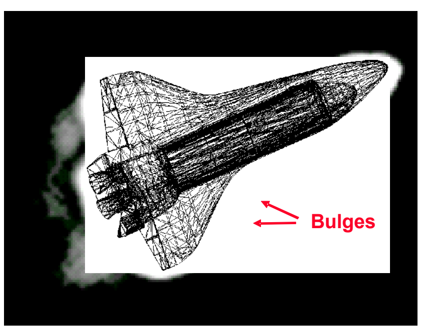

Two Bulges on Wing (B)

- Clearly outboard of wing - structure
- Shape is inconsistent with wing leading edge
- Inconsistent with flow pattern on right wing

Possible Causes

- Localized intensity increase
- Anomalous gas flow pattern

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Still at 13:57:14

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Preliminary

Localized intensity increase

- Local increase in temperature; hot spots
- Local increase in reflectivity (orbiter is in sunlight at this t ime)
  - Exposure of metal
  - This is considered unlikely, but is possible

Anomalous gas flow pattern in front of wing

- Tile damage?
  - Possible, but unlikely to change bow shock and wing shock shape (per aerothermo team)
- Damage to wing leading edge?
  - Could change local bow shock and wing shock shape (per aerothermo team)
- Viewing geometry and refraction could contribute

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Still at 13:57:14

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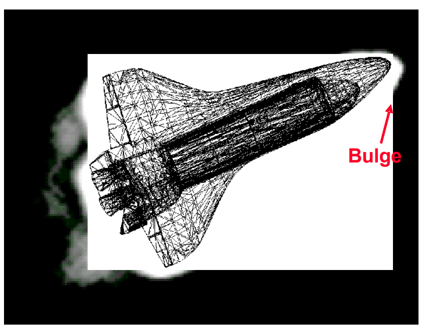
Preliminary



Asymmetry of Nose (C)

- Unknown if nominal
- Localized intensity increase
- Could be normal canopy shock seen from this angle
- Viewing geometry could hide symmetry

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Still at 13:57:14

Preliminary

Final Conclusions

- **Asymmetric gas behind left wing (A1)/brightened aft region(A2)**
  - Can be accounted for with structure of Orbiter
  - Contribution from leading edge "bulges" can not be ruled out
  - Contribution from elevon can not be ruled out
- **Bulges (B)**
  - Caused by either local increase in intensity or anomalous gas fl ow
    - Some possible causes of anomalous gas flow presented
      - » Modeling and wind tunnel testing investigations should aid in understanding and/or generate new theories
      - » Some measurements of angles of bulges in relation to orbiter may be possible if so requested by other teams
- **Nose asymmetry (C)**
  - Likely nominal condition
  - Flight data (OI and OEX) show no anomalous readings at the chin panel or vent nozzles at this time

Analyses of This Still is Considered Complete Unless Otherwise I nstructed

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Presenter Kandy Jarvis
Date April 21, 2003 Page 20

Frames at 13:57:54.14 & 13:57:54.22

Preliminary

- Notes Regarding Attitude Comparison at Time: 1 Feb 2003, 13:57:5 4 UTC
  - Telemetry exists for 13:57:54.14 UTC; 13:57:54.22 was interpolat ed.
  - Elevons, body flap, and engines are modeled in neutral position
  - Ground observer viewing from vertical tail and slightly to port
  - Model scales were done visually
    - Approximations were calculated based on wingtip to wingtip dista nce
    - Plate scale of still (5 secs later) known; compared to deconvolved image and plate scale approximated
    - Model fit visually based upon approximated scale.
  - Orientation (rotation) of frames with overlays were estimated ba sed upon known orientation of wireframe.

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Frames at 13:57:54

Presenter Kandy Jarvis
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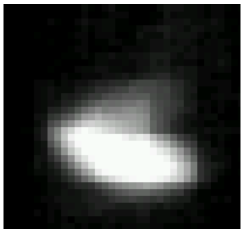
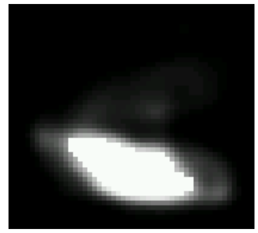
Preliminary

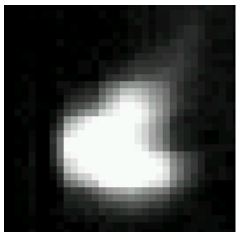


13:57:54.14

ß **Raw** **Re-Processed** à

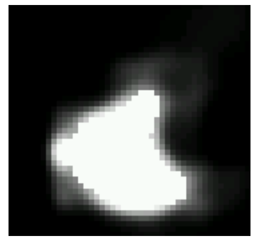


Note the "blocky" nature of the frames; this will generate some artifacts in the deconvolution process



13:57:54.22

ß **Raw** **Re-Processed** à



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Frame at 13:57:54.14

Presenter Kandy Jarvis
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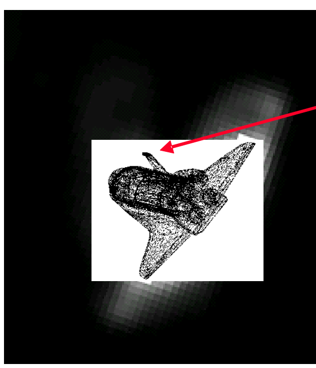
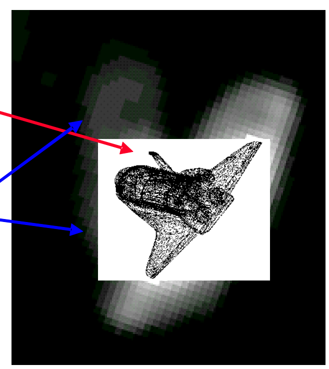
Preliminary



Tail

Artifacts?



Re-processed, rotated

Faint pixels enhanced

- Only wings clearly visible
- Nose or SILTS pod/tail faintly visible

Currently unknown if the enhanced pixels represent artifacts or flow features, etc. Modeling, wind tunnel testing, and processing of video should help determi ne this

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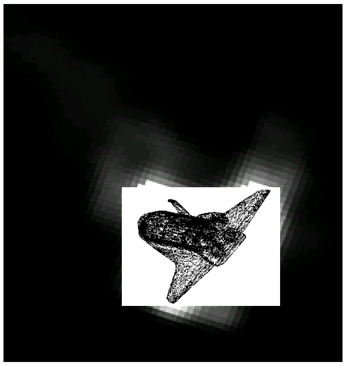
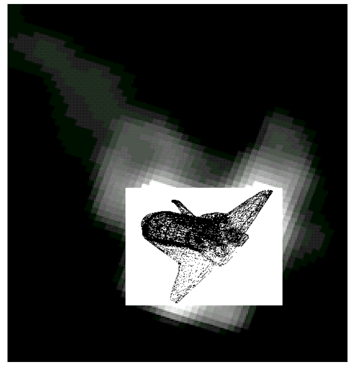
Frame at 13:57:54.22 (Flare Event #1)	Presenter Kandy Jarvis	
	Date April 21, 2003	Page 23

Preliminary



Re-processed, rotated



Faint pixels enhanced

•Increased intensity/visual blooming of nose or SILTS pod/tail
•Increased intensity/visual blooming of left wing

There are still multiple questions regarding the event seen here ; See discussion

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Frames at 13:57:54.14 & 13:57:54.22	Presenter Kandy Jarvis	
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Preliminary

Current understanding of video images

- The left wing appears to brighten
- The nose/tail then appears to brighten
  - Possible causes
    - Changes in the flow field for the left wing and tail
    - An event in the left wing generates a flow field that, at this v isual aspect, appears to intersect with the tail
      - Flow field is generally too faint to see but when additive with nose/tail brightness, appears to cause an overall brightening of the nose/ tail region
      - The tail passes through the flow field as the orbiter moves forw ard and this enhances the brightening
      - An illumination of the wing illuminates area(s) previously in sh adow (nose or tail)
    - There are no overt indications in information from the orbiter t hat suggests the tail underwent any change at this moment in time. Newly acq uired MADS data has not yet been compared against these times.
    - Diffraction (see next page)

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Frames at 13:57:54.14 & 13:57:54.22

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Preliminary

Diffraction:

- As a bright object exits the field of view of a telescope, diffr action of the optics can create a brightening of that object
  - Both "flare events" in the time line occur at the edge of the fi eld of view
  - SOR has taken video of Jupiter at the same angular size as the o rbiter, and moved the telescope so Jupiter left the field of view at the sam e approximate location as the orbiter
    - No flash or flare was seen to occur
    - Can not re-create phase angle of the sun at that time (no stars in daylight)
  - There does appear to be a distinct visual change in the orbiter between pre-flare and post flare. Still at 13:57:59 shows brightened nose/t ail region
- This suggests diffraction is not a cause of the events seen

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Still at 13:57:59

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Preliminary

- Notes Regarding Attitude Comparison at Time: 1 Feb 2003, 13:57:5 9 UTC
  - Telemetry unavailable for 13:57:59 UTC; interpolated.
  - Orientation known (rotation)
  - Elevons, body flap, and engines are modeled in neutral position
  - Ground observer viewing from vertical tail and slightly to port
  - Model scales were done visually
    - Approximations were calculated based on wingtip to wingtip dista nce
    - Plate scale of original known; compared to deconvolved image and plate scale approximated
    - Model fit visually based upon approximated scale

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Still at 13:57:59

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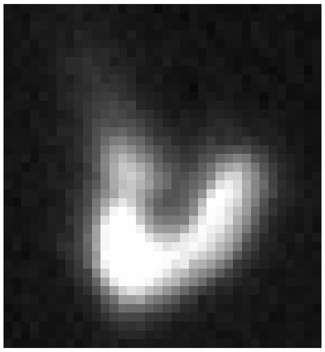
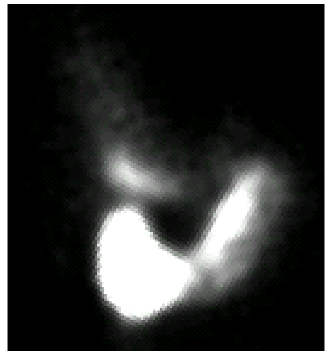
Preliminary



Raw Image in proper orientation



Re-Processed Image in proper orientation

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Still at 13:57:59

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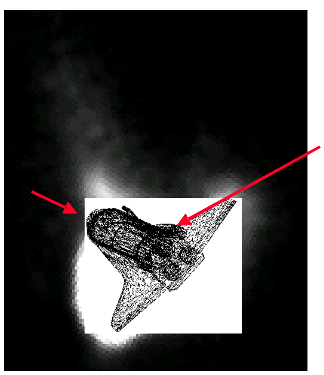
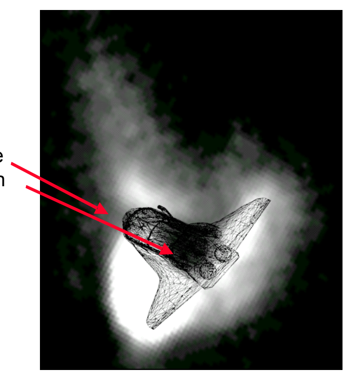
Preliminary



Re-processed

Shadowing
due to relative
location of sun



Faint pixels enhanced

The scale and exact placement of the wireframe overlay is still approximated

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Photo Still at 13:57:59

Presenter Kandy Jarvis
Date April 21, 2003 Page 29

Preliminary

Current understanding of still

- The left wing has increased intensity
- The nose/tail has increased intensity
  - Improved resolution (vs. video frames) suggests
    - An event in the left wing generates a flow field that, at this v isual aspect, appears to intersect with the tail
      - Flow field is generally too faint to see but when additive with nose/tail brightness, appears to cause an overall brightening of the nose/ tail region
      - An illumination of the wing illuminates area(s) previously in sh adow (nose or tail)
    - There are no overt indications in information from the orbiter t hat suggests the tail underwent any change at this moment in time

SPACE SHUTTLE PROGRAM
Space Shuttle Vehicle Engineering Office
NASA Johnson Space Center, Houston, Texas

Next Steps

Presenter Kandy Jarvis
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Preliminary

- SOR-AFRL Will
  - Provide video for plate scaling
  - Determine orientation of video frames of interest
- Acquiring Slightly Better Resolution Video Frames from Digital R ecording for Deconvolution
  - First set of frames have been acquired and will soon be processe d
- Continue Interpretation of Still 13:57:59 and Video Frames from 5 mRad Video
- Video Processing Will Search for Additional Signs of Debris
- Events Will Be Submitted for Entry Event Timeline as Confirmed

APPENDIX E
DEFINITIONS

Anomalous Optical Signature –A visual appearance of the orbiter containing a characteristic that appears irregular such as a lack of expected symmetry, pulsation of signal, or outline not matching the expected configuration.

Frames, Set of –A sequential subset of video frames extracted from the complete video, wherein the number of frames in a set varies according to the content.

Nominal –All conditions within normal expected parameters.

Off Nominal –A condition or conditions outside of normal expected parameters.

Orientation –The known compass direction of an image. This may be unknown due to the rotation of the imaging apparatus.

Pixel –A contraction of "picture elements"; a single energy flux detector.

Plate Scale –The ratio of a measurement on an image to the equivalent measurement of the imaged object.

Resample –An averaging of nearby values to generate a new value.

Resolution –The ability to separate closely spaced objects on an image.

Saturation –When the energy flux exceeds the sensitivity range of a detector or set of pixels. This overflow can also spread to adjoining pixels, altering their values.

Starfield –An image of a collection of identifiable stars at a known time that permits calculation of plate scale and compass orientation of an image.